Proton SEE Testing: Doing Correct Board Level Testing Correctly

Steven M. Guertin

Jet Propulsion Laboratory / California Institute of Technology

Pasadena, CA

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, Under contract with the National Aeronautics and Space Administration (NASA)

This work was sponsored by the OSMA/NASA Electronic Parts and Packaging (NEPP) program.

Acronyms

3D	Three Dimensional
CLK	Clock
cm	centimeter
e	Electron
FF	Flip Flop
HI	Heavy Ion
I	Input
IEEE	Institute of Electrical and Electronics Engineers
ISS	International Space Station
LET	Linear Energy Transfer
MeV	mega electron volts
mg	miligram
Mils	1000's of an inch
mm	micron/micrometer
n	Neutron, or n-type semiconductor
N	Number/Count
NASA	National Aeronautics and Space Administration
NC	no clock
NEPP	NASA Electronic Parts and Packaging Program
NSRL	NASA Space Radiation Lab
O	Output
p	Proton, or p-type semiconductor
r	resistance value, as in rsl, rbl, etc
R	Rate
RTG	Radioisotope Thermoelectric Generator
SEE	Single-Event Effects
SV	Sensitive Volume
TNS	Transactions on Nuclear Science
UC	University of California
X	Undefined
Z	Atomic Number

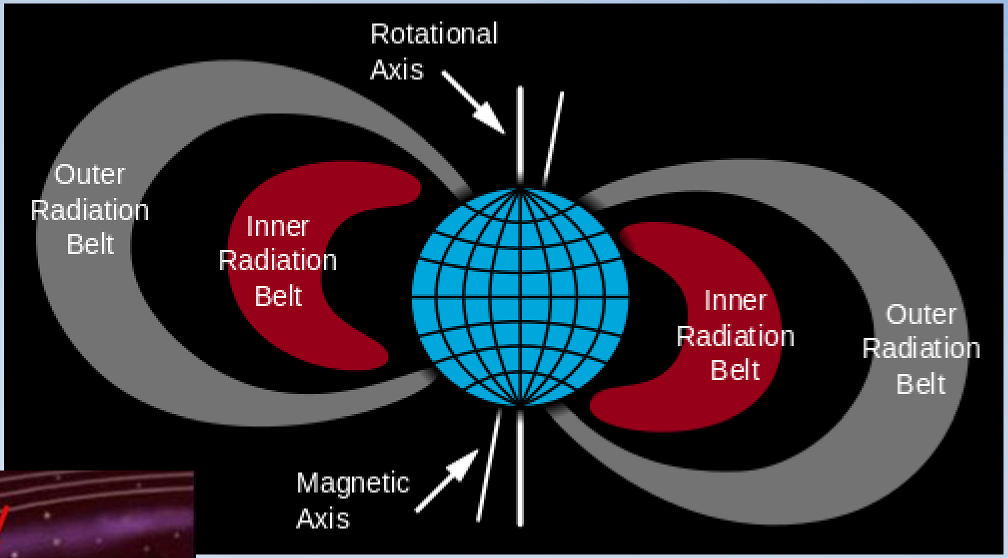
Outline

- Radiation Effects Review
- What is Board-Level Proton Testing
  - (What about Heavy Ions?)
- Why We’re Looking at This
- Proton Test Method
- Problems – w/Protons and General Issues
- How Do We Make It Better
- Conclusions

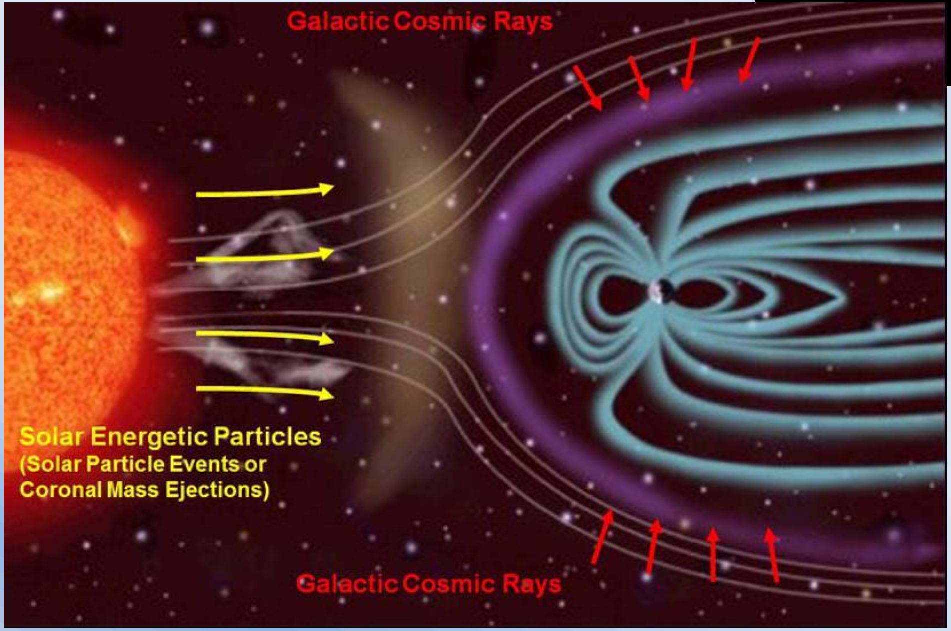
National Aeronautics
and Space Administration

(Ionizing)
Radiation Sources

Trapped Particle Belts →
e & p



Galactic Cosmic Rays
p & HI

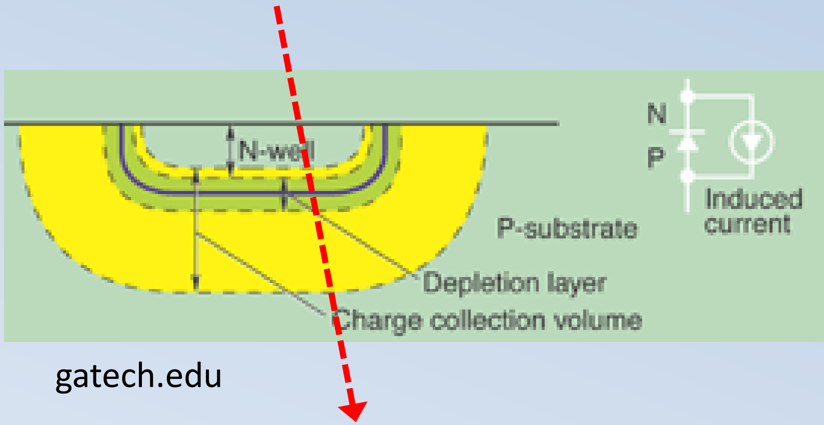


← Solar Particle Events
p, HI, X-Rays

Stuff we bring with us
n… X-Ray… ?
RTGs, instruments, …

Images from Wikipedia

Circuit Impact

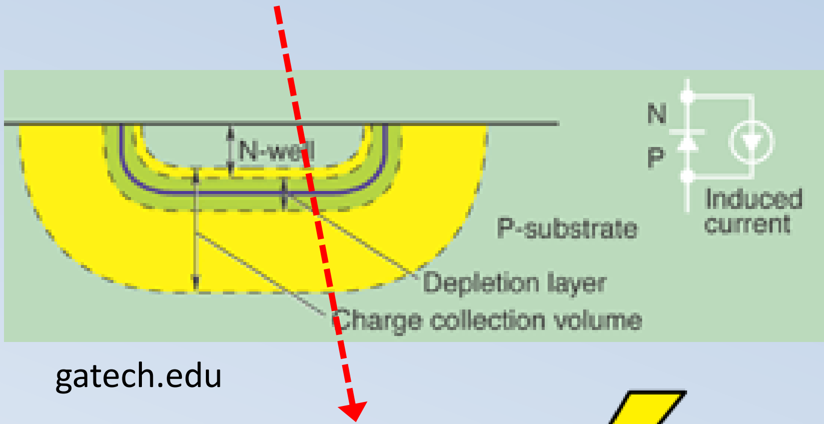


gatech.edu

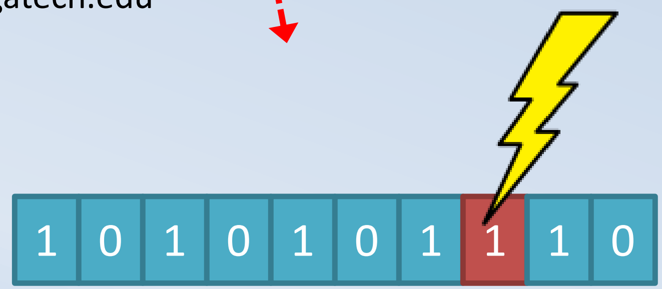
- Ionizing radiation leaves ionization trail through device
- Ion trail near diode junction can cause a transient current
- Depending on the circuit elements impacted, this can get locked in, or be detected as an edge

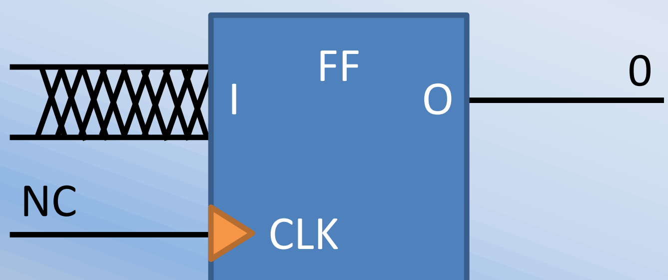
National Aeronautics
and Space Administration

Circuit Impact



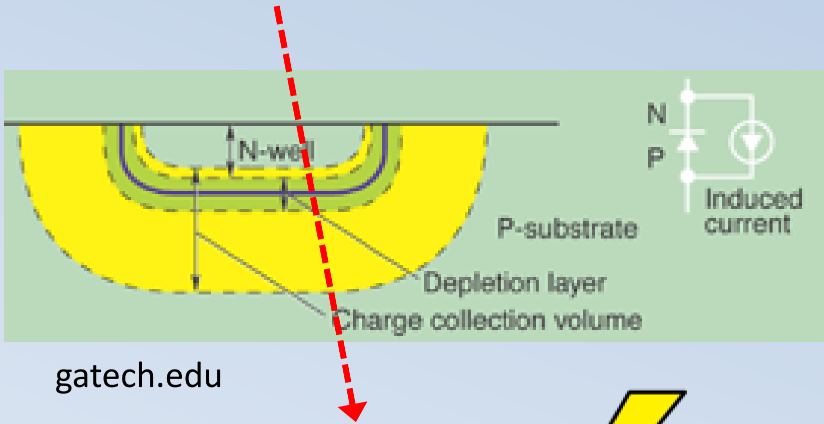
gatech.edu



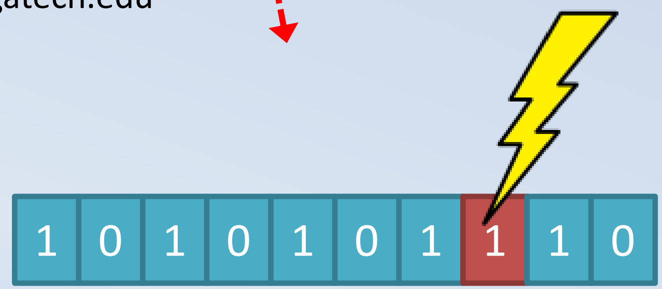


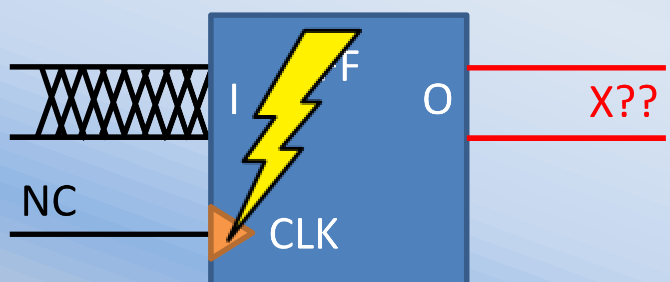
- Ionizing radiation leaves ionization trail through device
- Ion trail near diode junction can cause a transient current
- Depending on the circuit elements impacted, this can get locked in, or be detected as an edge

Circuit Impact



gatech.edu





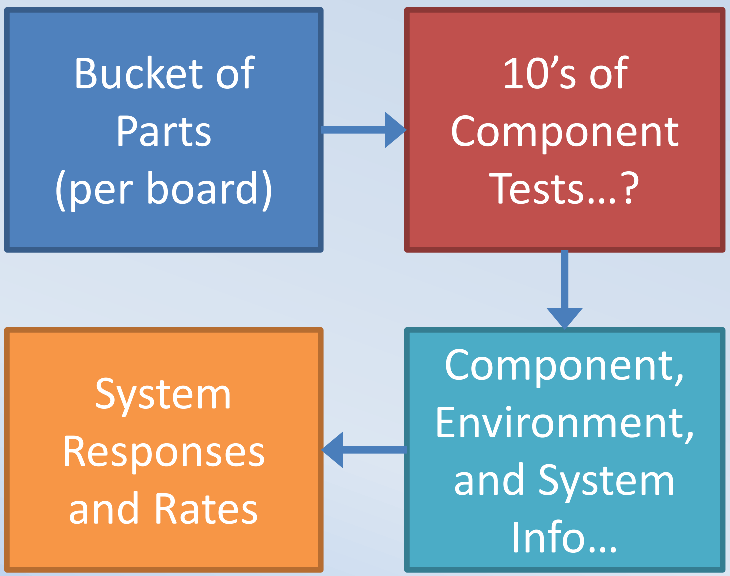
- Ionizing radiation leaves ionization trail through device
- Ion trail near diode junction can cause a transient current
- Depending on the circuit elements impacted, this can get locked in, or be detected as an edge

Evaluating Electronics

- Engineer determines what electronic components they want (may or may not have circuit figured out)
- Components are given as a list to a radiation engineer
- Potential issues are identified
- Radiation testing performed to worst-case boundaries
  - We use facilities that provide the key radiation effect in the critical part of the circuit
  - Space-like particles can go through inches of material
  - Ground-based proton facilities produce space-like protons (except for Jupiter… but still very similar)
  - Ground-based heavy ion facilities have very limited range – requires preparation of devices and theoretical support
- Radiation data and environment → space rates

Pressure to Adapt…

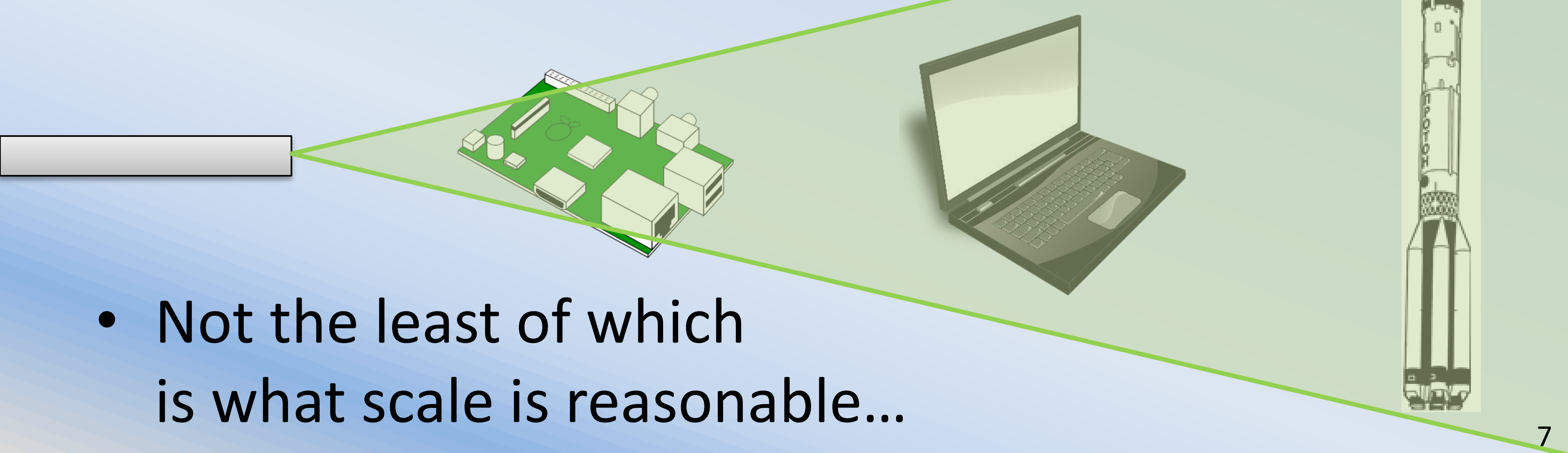
- Traditional approach expensive and conservative – and it may be outdated for modern systems



- Alternate approach of board-level testing is extremely attractive

New Approach(es)

- Should we evolve new test methods? See later…
- We're focusing here on board-level testing.
- … AND proton testing
  - – NEPP has been developing guideline for this testing
- Many questions…

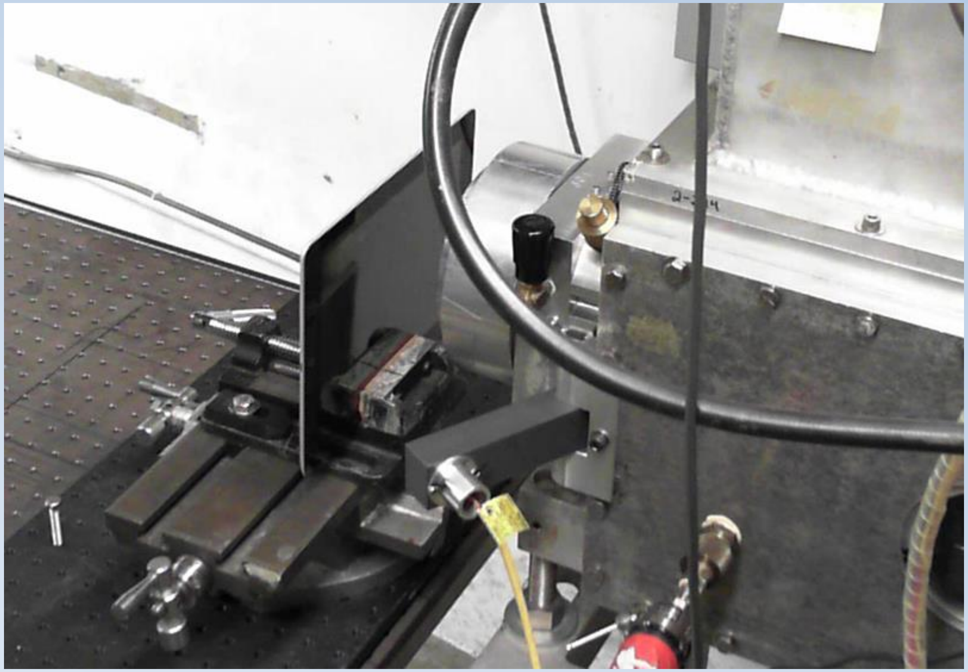


- Not the least of which
  is what scale is reasonable…

National Aeronautics
and Space Administration

Proton-Only Board Test NEPP Guideline

- Even for proton testing, doing testing, and applying results, is not trivial.
  - Adding heavy ions would help
- This is of … limited value
- And there are significant ways that tests can be of even less value
- NEPP is developing a proton board-level testing guideline to explore this problem



iPad irradiation at UC Davis

- See also the NEPP low-energy proton test guideline: http://radhome.gsfc.nasa.gov/radhome/papers/MRQW2012_Pellish.pdf
- (NEPP also currently working on Board Level Reliability for Ics “lessons” document.)

National Aeronautics
and Space Administration

More Later…

Why Is It Hard To Do Right?

- Proton Specific –
  - Only gives about 10x reduction [relative to no testing] in rates in the weakest environments (ISS)
  - Using protons for heavy ions has poor theory support
    - Linear energy transfer (LET) not well defined
- Board-Level General –
  - Scaling with size of system is non-trivial
  - Only test-as-you-fly makes sense (which we can't do)
  - Board-level error modes are very hard to track to individual components

What About: Heavy Ions?

- The background and focus of this material is proton testing…
- Heavy Ion testing can also be done at the board-level
  - Absolutely unreasonable to delid multiple parts on one board (as required for most ground facilities)
    - Success of delidding a component on a board ~20-80%... Multiple deliddings guarantee failure
  - NASA Space Radiation Lab (NSRL) at Brookhaven
    - Delidding not needed
    - Only reasonable facility to do testing in US
  - Angular theory on protons is actually better than higher energy heavy ion facilities…

Motivation: Why?

- Proton-only testing is being used by…
  - Higher risk NASA missions
  - Aggressive commercial
  - Evolve new methods?
- General board-level testing considered for same reasons, and:
  - Enable use of new, high-performance boards
  - Future radiation testing issues…

CubeSats deployed from ISS

Motivation: Future

- Not likely to go away:
  - Package on Package
  - Limited beam penetration on 3D Circuits
  - Heat sinks and thermal management
- Mission design
  - If limitations are understood, design could benefit
- We should establish best practices in the use of proton (and general) board-level testing.

What is Proton Only Test Method?

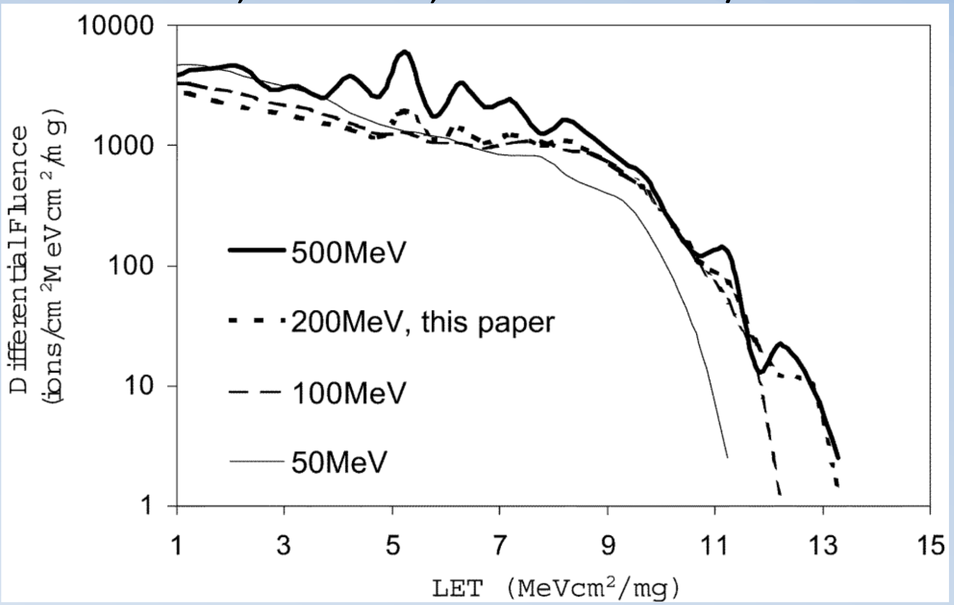
- Essentially, you only do a proton test of an entire board or subsystem, instead of testing components.
  - Hits everything all at the same time
- Uses 1×10^{10} protons/cm^2 (with ~200 MeV)
  - Limits total dose while providing sensitivity to SEE
  - Gets up to somewhere between 2 and 12 LET, with a lot of argument
  - Increased exposure enticing, but TID is significant problem
- Relies on application to relatively weak radiation environments
  - Only really applied to ISS orbit – but limited by NASA to non-critical systems
  - Might actually be slightly better for low inclination LEO and Mars surface (but not studied yet).

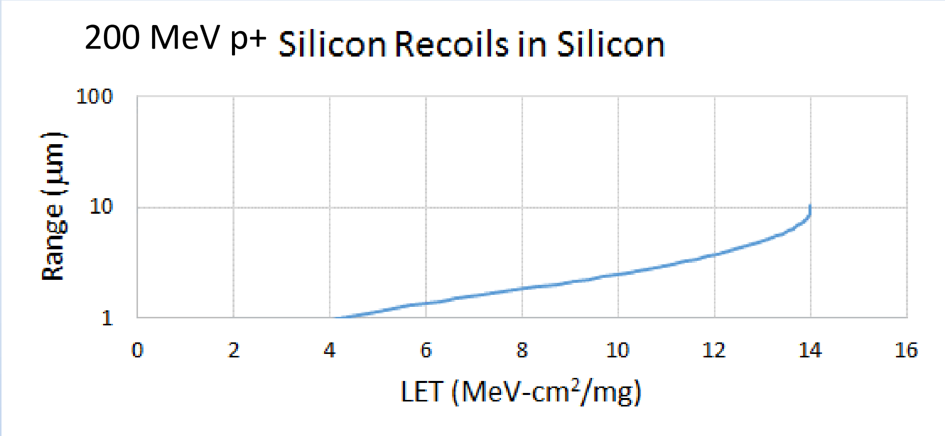
National Aeronautics
and Space Administration

Proton Theory

- Protons do (sort-of) simulate the environment
  - Nuclear reactions
  - ISS environment simulated up to a rough cutoff
  - Results can be applied to other environments
    - Understand sensitive volumes (SVs)
    - Environment heavy ions
- But reaction particles are inherently short-ranged
  - Extremely not space-like

Heimstra, IEEE TNS, 2003 – $1\times10^{10}/cm^2$

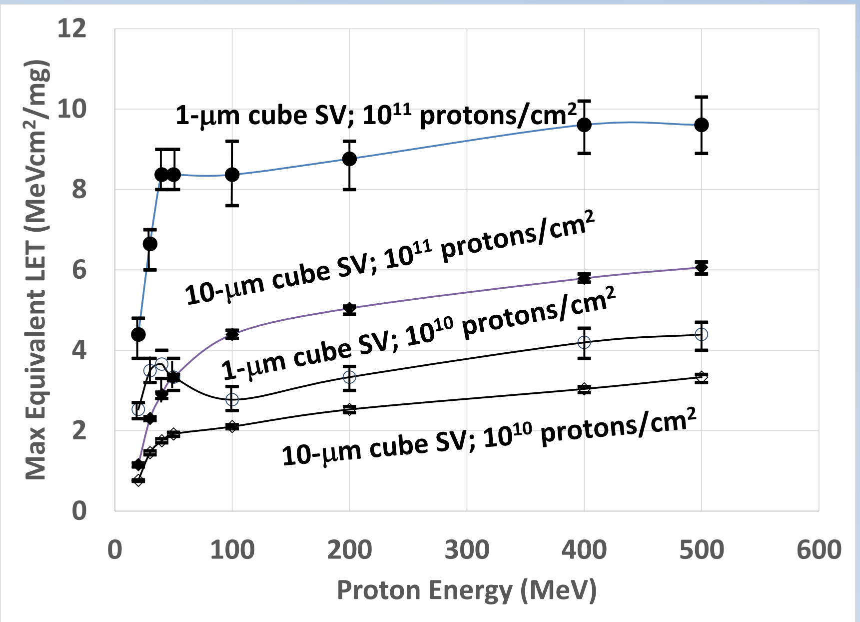




National Aeronautics
and Space Administration

Equivalent LET
What are the protons doing?

- Thickness of the charge collection region is critical for proton testing…
- There are some parts with failure rates around 0.1/device-day in ISS orbit. You're here without test data.
  - Worse for most environments
- With proton testing, 1e10/cm^2 results in destructive SEE rates around 0.01/device-day
  - 1e11/cm2 improves this, but hard numbers are limited



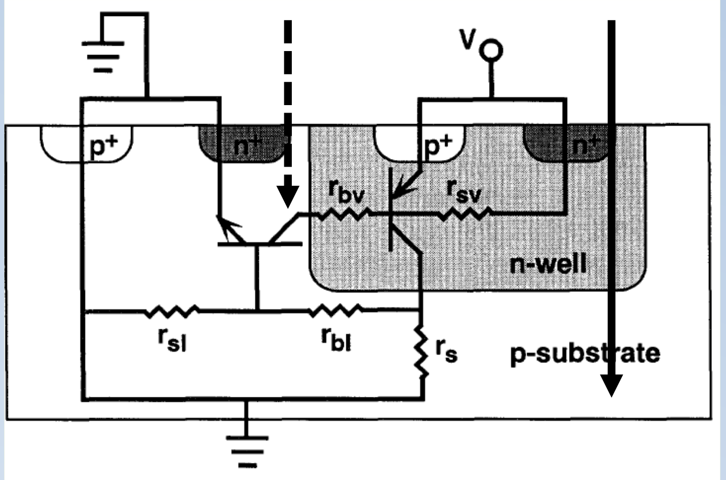
Ladbury, IEEE TNS, 2015

Equivalent LET = Energy / (ρ*d_{SV})
Max Equivalent LET requires 2.3 recoils

National Aeronautics
and Space Administration

Protons Are Not Great

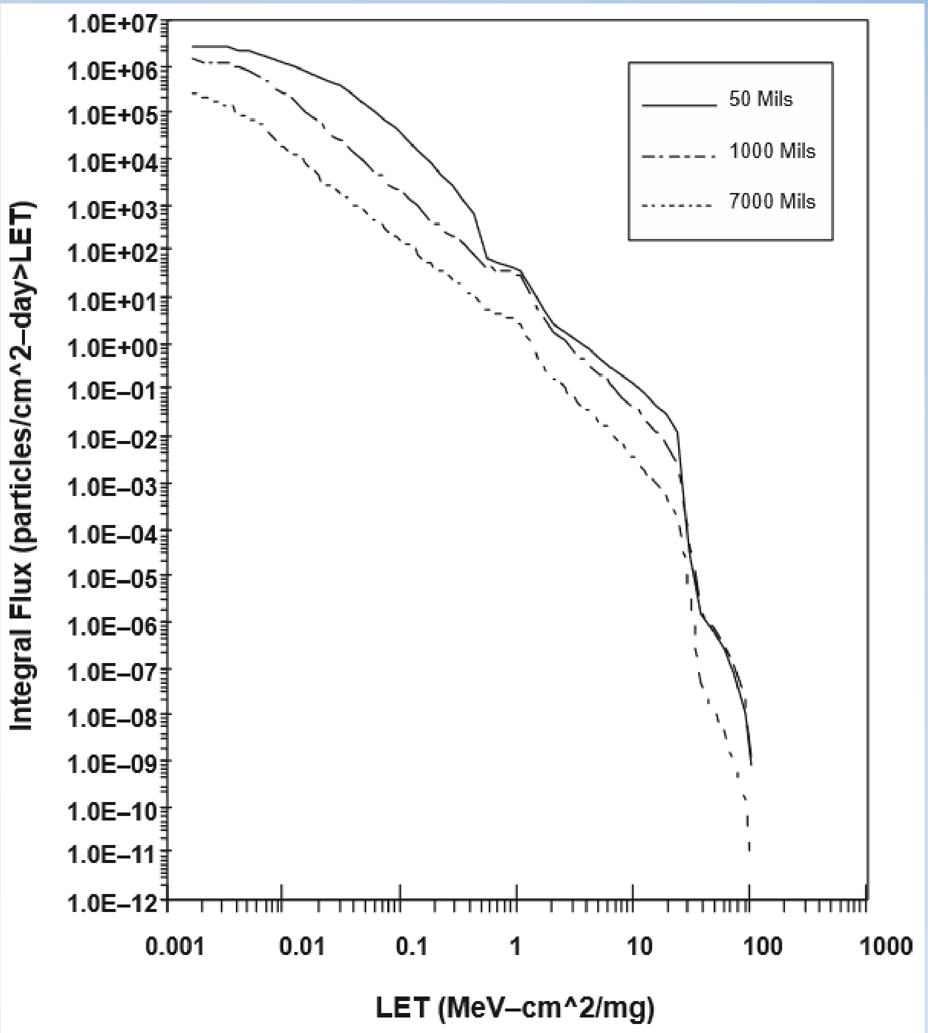
- The SEEs proton testing is worst for, are the worst things:
  - Latch Up
  - Burnout
  - Gate Rupture
- Ions generated are low(er) Z
- Ion range limited to ~10µm
- May be difficult to observe and isolate rare events from test artifacts
- Also difficult or impossible to determine failing part(s) – could be anything on the board.



SEL in pnpn structure - Ladbury, 2015

Using Results Is Tricky

- But it does work – a little
  - What you're getting is so minimal that **a bad test or misinterpretation could be worse than no test**
- The results are not great
  - At 1×10^{10} fluence, resulting damaging SEE rate is only constrained to 0.01/day (worst case, due to bad actors) – For ISS orbit
  - 1×10^{11} does much better, but not quite 10x better, on average

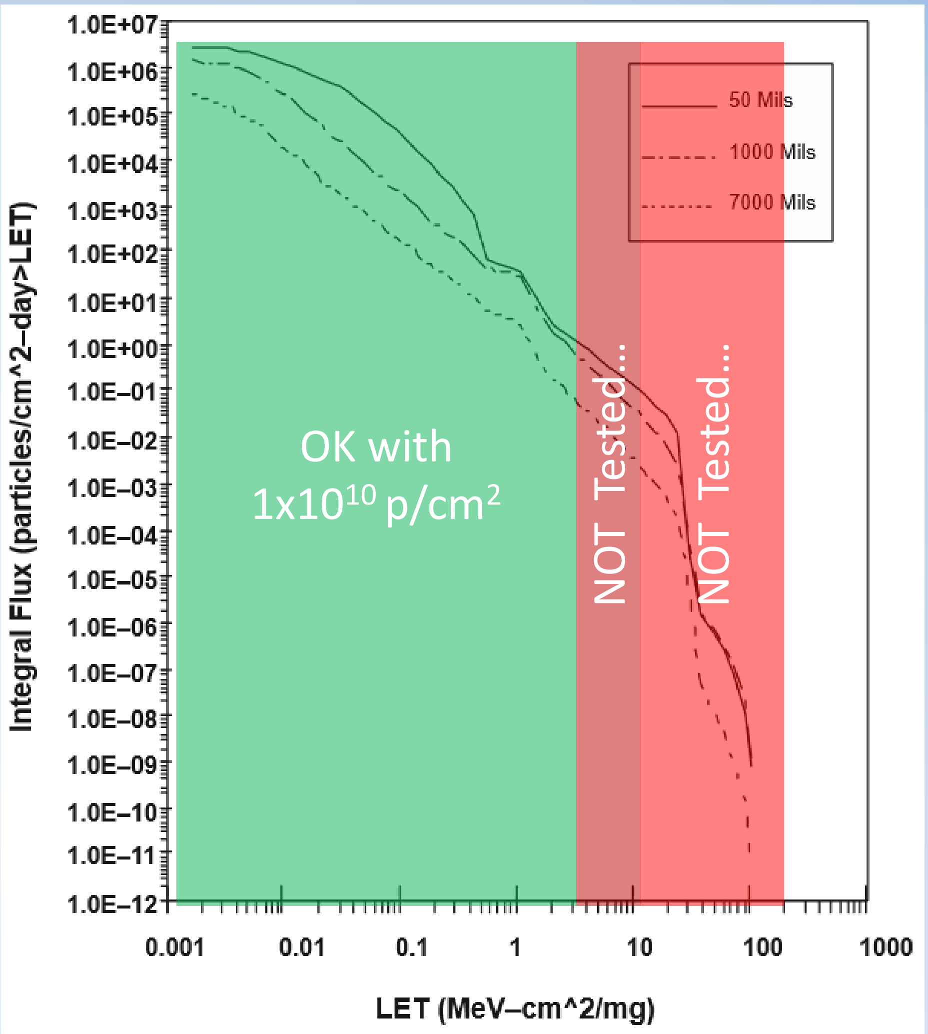


ISS Particle Environment Boeder, 1994

National Aeronautics
and Space Administration

Using Results Is Tricky

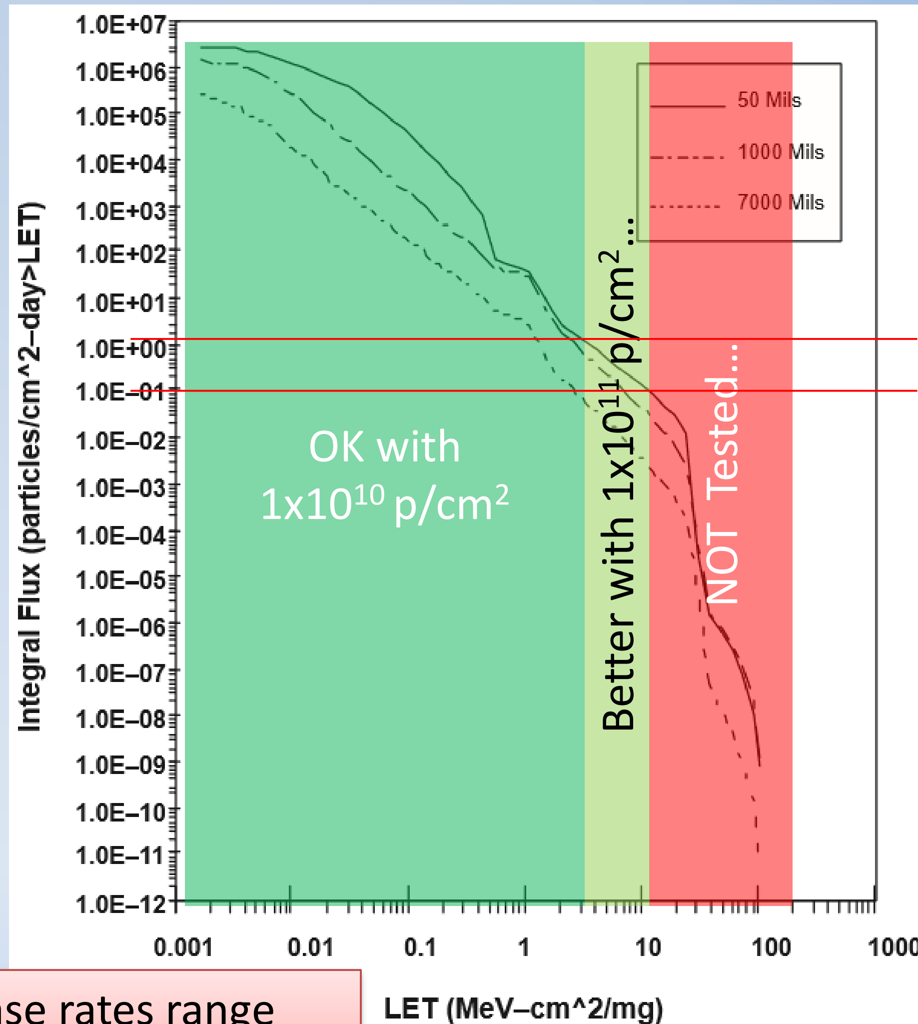
- But it does work – a little
  - What you're getting is so minimal that **a bad test or misinterpretation could be worse than no test**
- The results are not great
  - At 1×10^{10} fluence, resulting damaging SEE rate is only constrained to 0.01/day (worst case, due to bad actors) – For ISS orbit
  - 1×10^{11} does much better, but not quite 10x better, on average



ISS Particle Environment Boeder, 1994

Using Results Is Tricky

- But it does work – a little
  - What you're getting is so minimal that **a bad test or misinterpretation could be worse than no test**
- The results are not great
  - At 1×10^{10} fluence, resulting damaging SEE rate is only constrained to 0.01/day (worst case, due to bad actors) – For ISS orbit
  - 1×10^{11} does much better, but not quite 10x better, on average

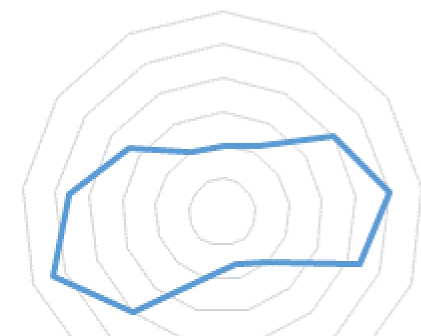


Worst-case cross sections are ~0.01… so worst case rates range from 0.01/system day with 1×10^{10}, and ~3-10x better for 10^{11}…

…le Environment Boeder, 1994

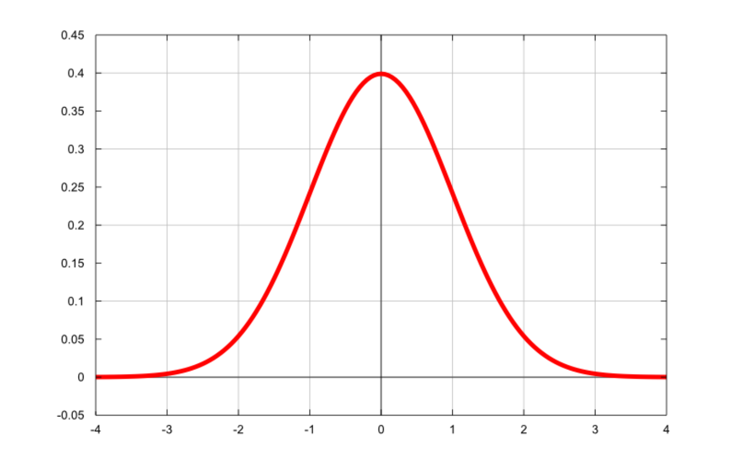
Other Theory Issues

- Angular theory is frustrating
  - Proton recoils have flat angular distribution – so they are GOOD for testing angular response
  - If something does happen, you know little about angle of the ion that caused it (if you care)



Sampled well with proton recoils, hard to test with HI...

- Most frustrating: It is probably, on-average, much better than the worst-case established...
  - How likely are worst-case devices? – is the method still intrinsically very conservative

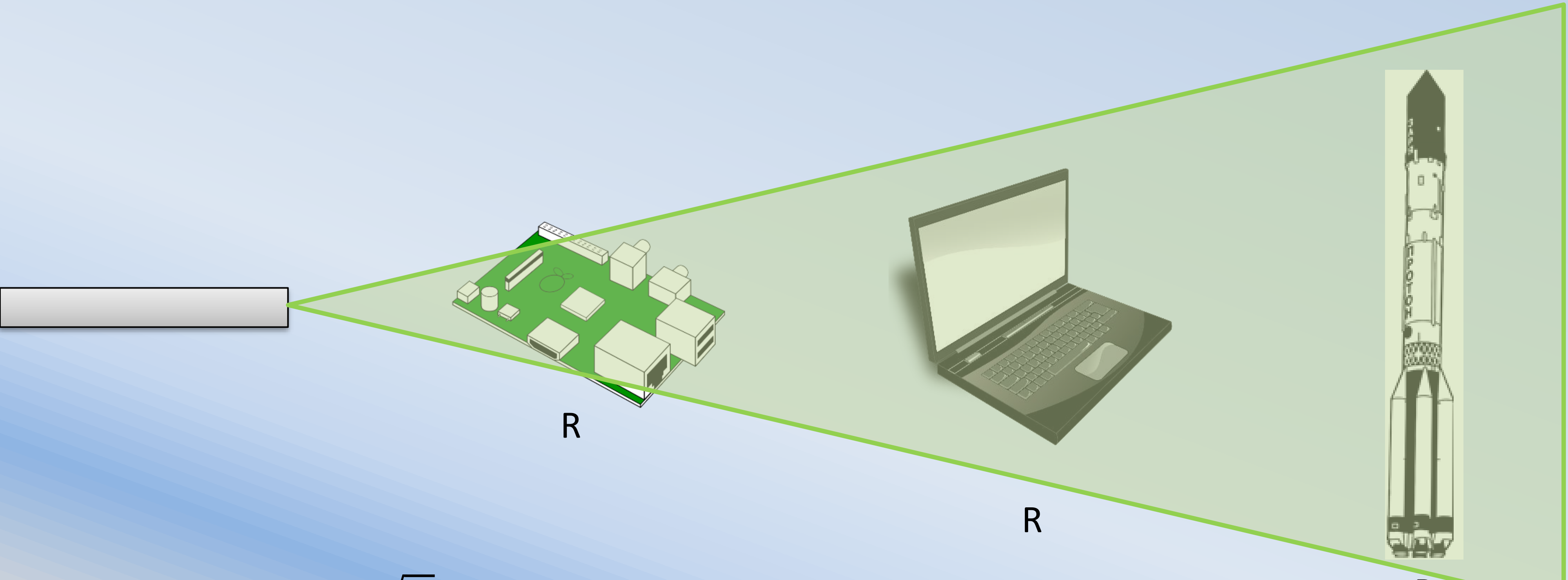


Test Coverage

- Proton testing actually gives very few HIs
  - 1×10^{10} p/cm^2 (200 MeV) only gives about 3.5×10^4 recoils – across all LETs
  - Usually, for lower LET ions, we prefer to test with at least 1×10^7 #/cm^2 to have a good idea what the sensitivity is.
  - Here the HIs are split across many LETs
- Also, different SVs will have different LET spectra for the same recoil spectrum
  - Due to different SV depths – long SVs will have lower LET_{EFF}
  - So you are mixing different event types
- This low number of recoils means you are missing essentially large functional structures in modern devices
  - As a side-note, this also impacts heavy ion testing. – Heavy ion testing is now missing large/functional structures.

HI & p: Test Scaling

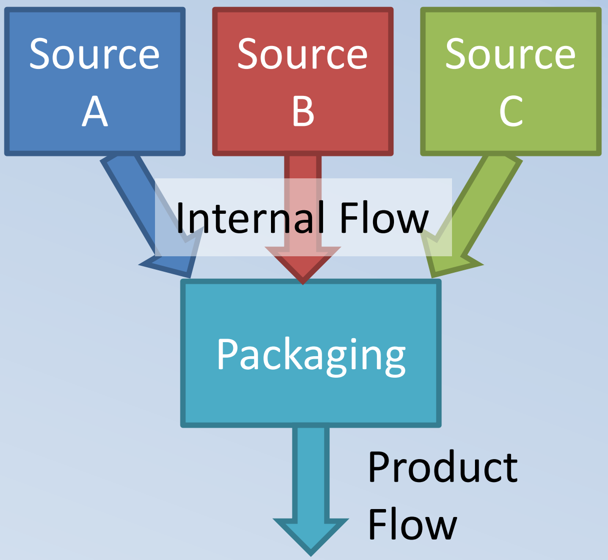
- Test results are not well-defined, because system size can be arbitrary
  – Assume the test results in a system rate of R…



Or…$R\sqrt{N}$? With N something like the number of circuits

The Bad Link Between Test and Flight

- Most commercial vendors do not have parts tracking programs… extra cost with no benefit
  - We (rad group) recently sent some boards out for fabrication with test parts and the fab house wanted to (without telling us) replace our test parts
- Commercial boards are usually made with at least some uncontrolled source components
  - Board fab may not even control which vendor
- Commercial components may change fabrication facilities or revisions on 3-month timeframes.
- It is possible to engage people to improve this…
- And it is possible to develop some guidelines regarding how different parts' SEE performance may be related…



This happens at component and board assembly levels.

In some cases there is no Internal tracking.

Part-to-Part Variation

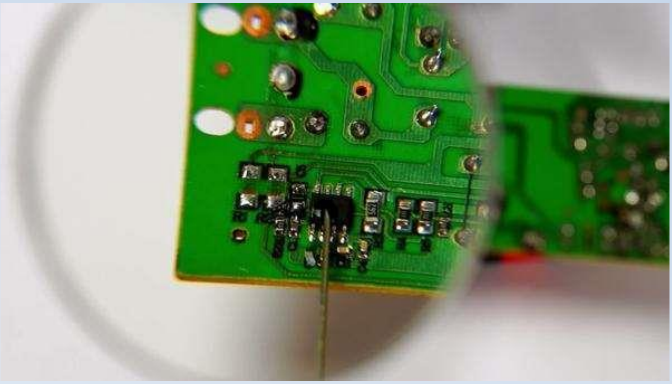
- The link between test and flight essentially comes down to making sure the same parts are tested as flown.

- But even if the parts are the "same" there may still be lot-to-lot variation.
  - Just to reiterate, it is possible that an identical lot of commercial devices may be sourced from three different fabrication facilities.
  - Fabless manufacturers are making this problem harder.

- This is essentially intractable without working with the board and component vendors.
  - A "stab" could be made at how wide the variation may be, and how many boards/systems need to be tested to identify the distribution.
  - You could use the bimodal lot approach from TID testing, which says you need to test ~45 boards.
  - But what stops manufacturer from changing parts?

You Need to Know A Lot

- Board-Level Testing ≠ No Radiation Engineering
- The only way it's easy is if the test is go/no-go
  - But given the position late in the design/review phase, this is not viable
- Instead, you need understanding of both the circuit and the potential SEE effects
  - Radiation engineer can help identify likely weak spots early…
  - And circuit engineer can provide details about circuit when failures occur.
  - Solving failures can be carried out between both disciplines…
    - Example – circuit with potentially weak MOSFETs called out – discussed with designer who indicated the devices were used outside of the radiation safe operating area (SOA) – when failure occurred it was relatively easy to replace the failing components.
    - Otherwise, it's finding a needle in a haystack…



How Do We Make It Better? (1 of 2)

- (Take for a given, that we should do this.)
- Feedback on effectiveness is essential
- Figure out how to test boards/systems identical to flight boards/systems
  - Work with component manufacturers (some components will be impossible to verify)
  - Run boards in flight-like configuration
    - Requires flight-like software and firmware, both of which are not current paradigm
- Engage community to develop this as a research area…

Improve Theory

(including empirical methods)

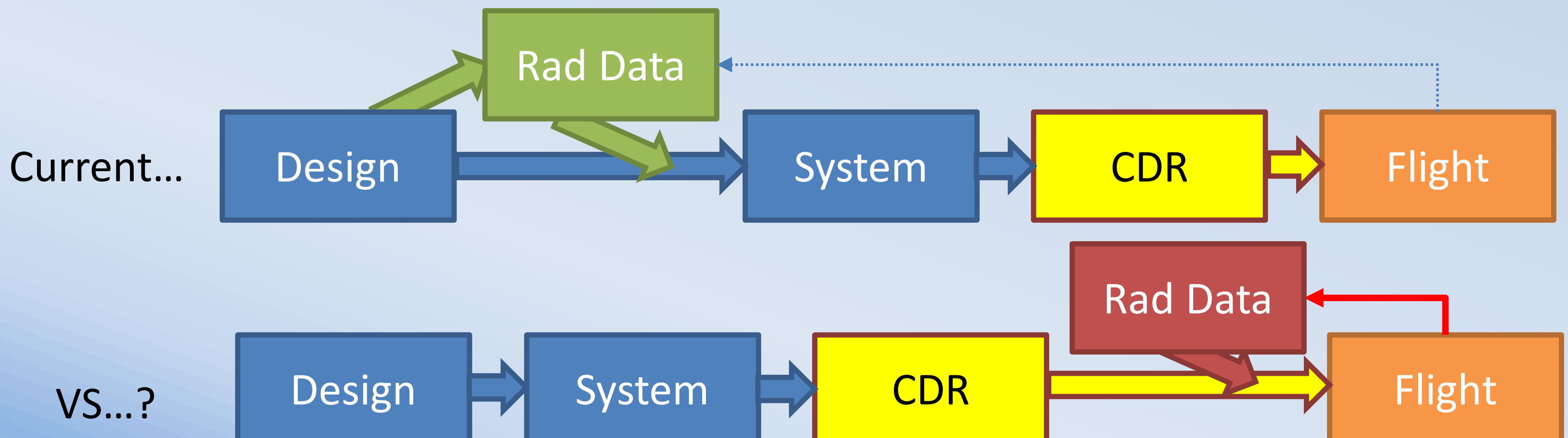
Build/Improve database of component behaviors

Flight feedback from larger community

How Do We Make It Better? (2 of 2)

- Build system models and statistical methods to maximize value from data
  - For example, best usage may be when building multiple "identical" spacecraft which can sample different configurations and components

- How do we handle not having data early in the design phase?



Conclusion

- Normal approach for testing – test at component level
  - Expensive, time-consuming, conservative, outdated (?)
  - Other groups in the industry (newer especially) are moving away
  - Mostly, board-level testing is about reducing cost

- Easy to do board-level testing wrong, and lots of difficulties with the methods
  - Theory is not there – test experience is primary driver
    - May be critical to show theory is right and proton-only method is very limited
  - Connecting board-level tests to flight boards is very important
  - Other issues… have to have good working knowledge of likely events, need board level models, etc…

- The biggest problem, going forward, is how to support people doing board-level testing. Or relegate the method to high risk, short missions only.
  - Improved feedback between tests and flight experiences
  - Improved databases because the (proton) method is empirically-based

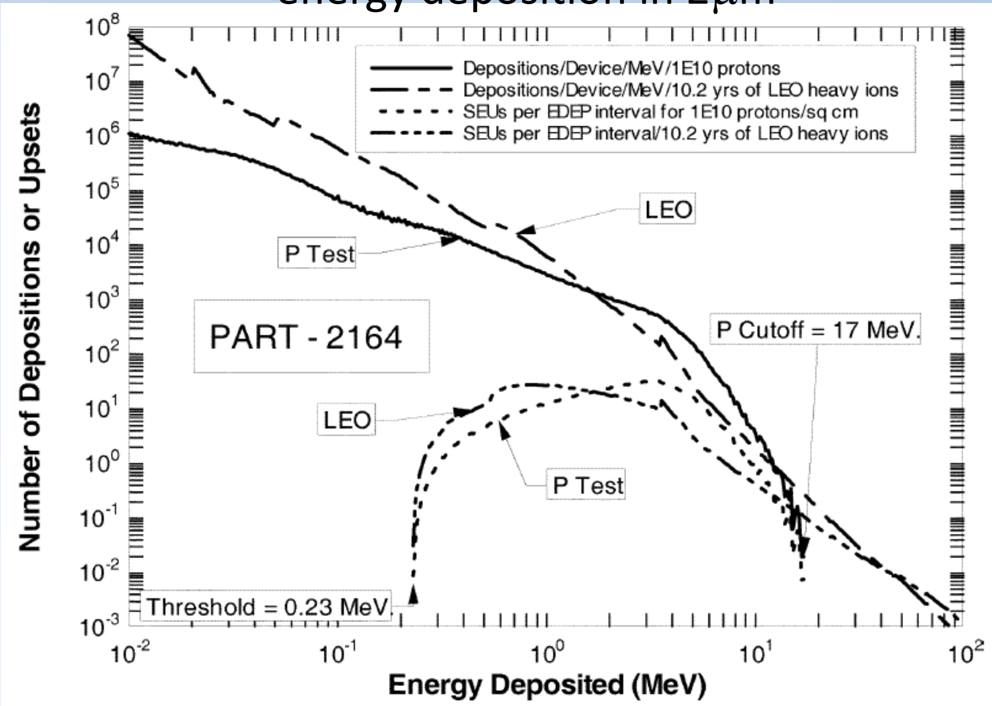
END

National Aeronautics
and Space Administration

Protons Have Limitations

- In a 2μm sensitive depth…
  - $1 \times 10^{10}/cm^2$ 200 MeV Protons
  - More protons can be used
- Proton recoils give energy depositions similar to heavy ions
  - But leave high LET gap
  - More protons weakly affect the gap region
- But not all SEE modes are this shallow
  - More later

Foster, IEEE TNS, 2008 –
energy deposition in 2μm

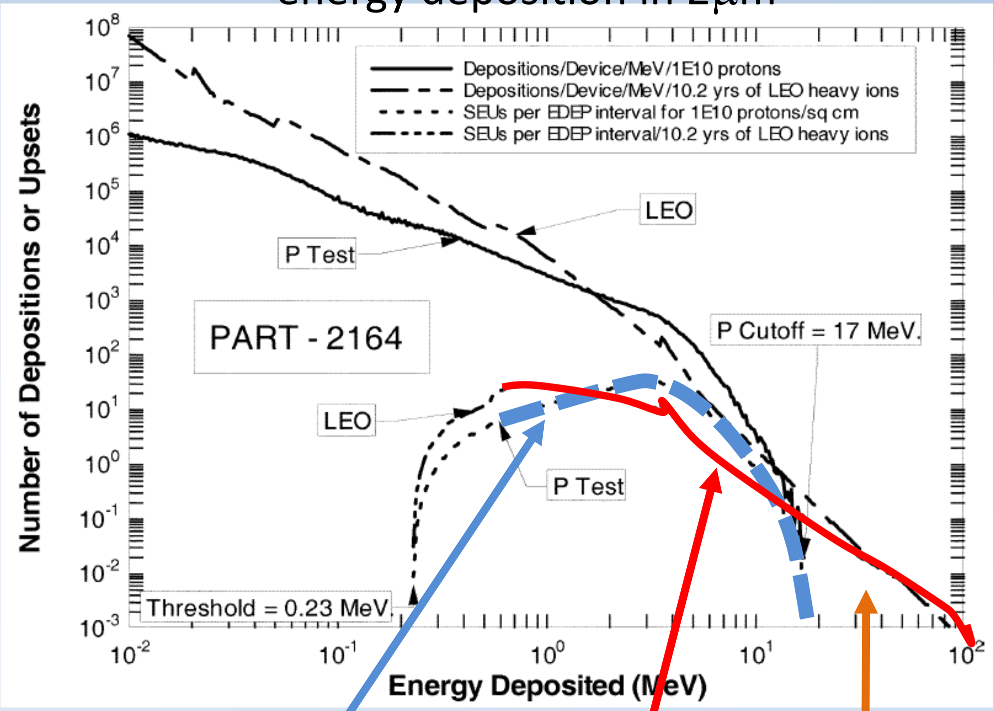


National Aeronautics
and Space Administration

Protons Have Limitations

- In a 2μm sensitive depth…
  - $1\times10^{10}/\text{cm}^2$ 200 MeV Protons
  - More protons can be used
- Proton recoils give energy depositions similar to heavy ions
  - But leave high LET gap
  - More protons weakly affect the gap region
- But not all SEE modes are this shallow
  - More later

Foster, IEEE TNS, 2008 –
energy deposition in 2μm



Events during proton testing

Events during 10 year ISS mission

Gap

Similar to LET 14